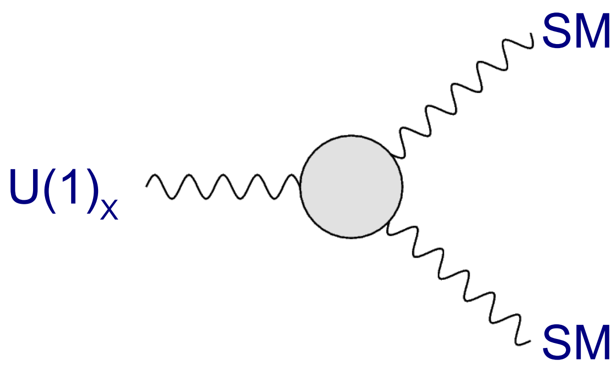
Fermiophobic gauge bosons as an effective theory at the LHC

A common extension to the Standard Model is the addition of new U(1) gauge groups. These occur naturally in grand unified models and string models involving “intersecting branes”.

$$SO(10) \rightarrow (SU(3)_c \times SU(2)_L \times U(1)_Y) \times \underline{U(1)_X}$$

$$E_6 \rightarrow SO(10) \times \underline{U(1)_X}$$

We will explore the phenomenology of an extra U(1) which couples to the SM through 3-boson couplings

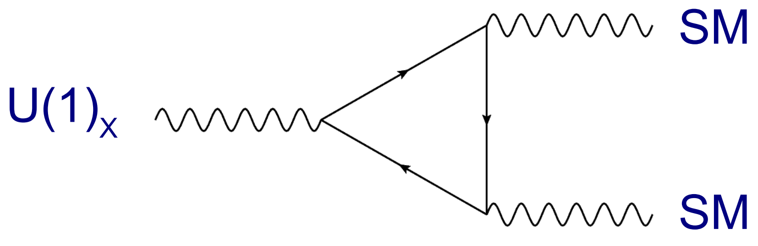


Why 3-boson couplings?

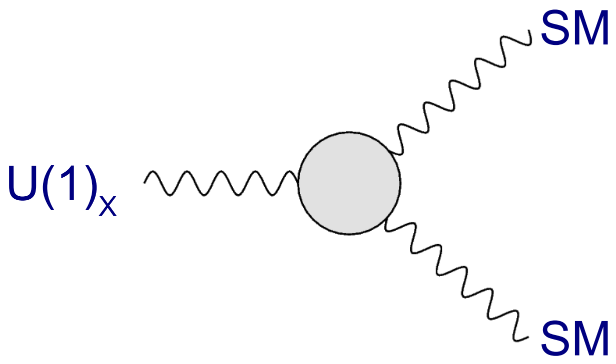
Let us imagine an extra U(1) where...

- The X boson acquires mass at a scale within reach of current colliders
- SM fermions are neutral under $U(1)_X$... hence, "fermiophobic"
- There exist heavy fermions charged under both $U(1)_X$ and the SM gauge groups

These new fermions are hidden at low energies, but can couple the X-boson to the SM through loops.

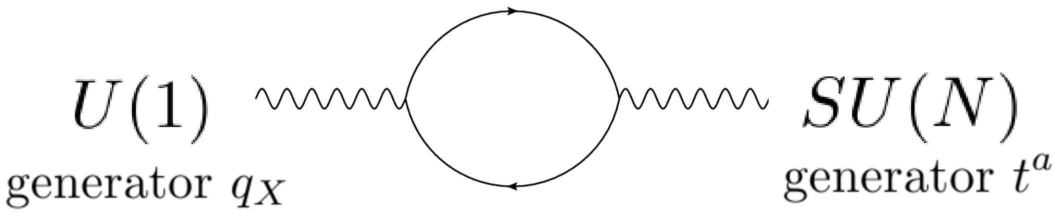


By integrating out the fermions, we are left with an effective operator with coupling set by the high energy theory

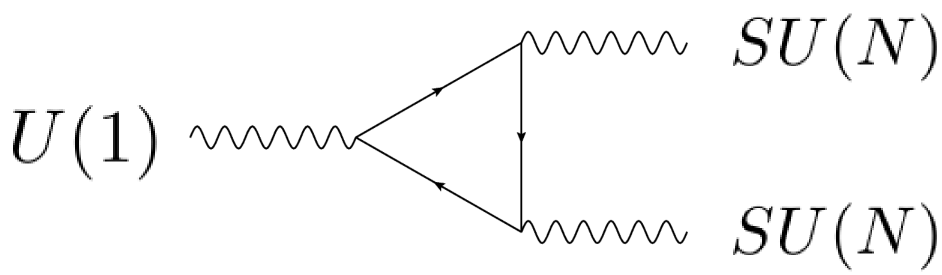


Why 3-boson couplings?

Kinetic mixing not allowed between U(1) and SU(N)



$$\text{Amplitude} \;\propto tr[q_X t^a] = 0$$



$$\text{Amplitude} \;\propto tr[q_X t^a t^b] \propto q_X \delta^{ab}$$

The Effective Operator Approach

Xgg Coupling

We can use $SU(3)_c$ gauge invariance to write all possible parity-odd operators in terms of gluon field strength...

$$\mathcal{O}^1_{Xgg} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta}X_\mu D^\nu G^a_{\alpha\nu}G^a_{\beta\rho}$$
$$\mathcal{O}^2_{Xgg} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta}\partial^\nu X_\mu G^a_{\alpha\nu}G^a_{\beta\rho}$$
$$\mathcal{O}^3_{Xgg} = \frac{1}{\Lambda^2}\epsilon^{\alpha\beta\nu\rho}\partial_\mu X^\mu G^a_{\alpha\beta}G^a_{\nu\rho}$$

The lowest dimension operators we can write are of dimension 6.
Higher dimensional operators can be written, but are suppressed by $1/\Lambda^4$

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For X on-shell, momentum orthogonal to polarizations...

$$= 0$$

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$$\mathcal{O}^2_{Xgg} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta} \partial^\nu X_\mu G^a_{\alpha\nu} G^a_{\beta\rho}$$

In X rest frame, after some index juggling and utilizing antisymmetry of epsilon,

$$= 0$$

The Effective Operator Approach

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$$\boxed{\mathcal{O}^1_{Xgg} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta} X_\mu D^\nu G^a_{\alpha\nu} G^a_{\beta\rho}}$$

This is the only possible parity odd Xgg coupling of dimension ≤ 6

The Effective Operator Approach

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$$\boxed{\mathcal{O}^1_{Xgg} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta} X_\mu D^\nu G^a_{\alpha\nu} G^a_{\beta\rho}}$$

Vertex operator:

$$\Gamma^{Xgg}_{\mu\nu\rho}(k_X, k_1, k_2) = \frac{1}{\Lambda^2}\left[\epsilon_{\mu\nu\rho\sigma}(-k_1^2 k_2^\sigma + k_2^2 k_1^\sigma) + \epsilon_{\mu\rho\sigma\tau} k_{1\nu} k_2^\sigma k_1^\tau - \epsilon_{\mu\nu\sigma\tau} k_{2\rho} k_2^\sigma k_1^\tau\right]$$

The Effective Operator Approach

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Vanishes for gluons on-shell:

$$\epsilon_1^\nu k_{1\nu} = 0 \qquad \epsilon_2^\rho k_{2\rho} = 0$$

This is in accordance with the Landau-Yang theorem

(A massive spin 1 particle cannot decay to 2 massless spin-1 particles)

Electroweak Effective Operator

XVV Electroweak Coupling

Many possible terms...

X Z Z

$$\mathcal{O}^1_{XZZ} = \epsilon^{\mu\nu\rho\sigma} X_\mu Z_\nu Z_{\rho\sigma}$$
$$\mathcal{O}^2_{XZZ} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta} X_\mu \partial^\nu Z_{\alpha\nu} Z_{\beta\rho}$$
$$\mathcal{O}^3_{XZZ} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta} \partial^\nu X_\mu Z_{\alpha\nu} Z_{\beta\rho}$$
$$\mathcal{O}^4_{XZZ} = \frac{1}{\Lambda^2}\epsilon^{\alpha\beta\rho\sigma} \partial_\mu X^\mu Z_{\alpha\beta} Z_{\rho\sigma},$$

X Z γ

$$\mathcal{O}^1_{XZ\gamma} = \epsilon^{\mu\nu\rho\sigma} X_\mu Z_\nu F_{\rho\sigma}$$
$$\mathcal{O}^2_{XZ\gamma} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta} \partial^\nu X_\mu (Z_{\alpha\nu} F_{\beta\rho} + F_{\alpha\nu} Z_{\beta\rho})$$
$$\mathcal{O}^3_{XZ\gamma} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta} \partial^\nu X_\mu (Z_{\alpha\nu} F_{\beta\rho} - F_{\alpha\nu} Z_{\beta\rho})$$
$$\mathcal{O}^4_{XZ\gamma} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta} X_\mu \partial^\nu Z_{\alpha\nu} F_{\beta\rho}$$
$$\mathcal{O}^5_{XZ\gamma} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta} X_\mu \partial^\nu F_{\alpha\nu} Z_{\beta\rho}$$
$$\mathcal{O}^6_{XZ\gamma} = \frac{1}{\Lambda^2}\epsilon^{\alpha\beta\nu\rho} X^\mu \partial_\mu Z_{\alpha\beta} F_{\nu\rho}$$
$$\mathcal{O}^7_{XZ\gamma} = \frac{1}{\Lambda^2}\epsilon^{\alpha\beta\nu\rho} \partial_\mu X^\mu Z_{\alpha\beta} F_{\nu\rho}$$

Electroweak Effective Operator

XVV Electroweak Coupling

Alternatively, we can construct interactions with the *unbroken* SU(2) and U(1) fields. This is much simpler, because the operators must be **gauge invariant** in this formalism.

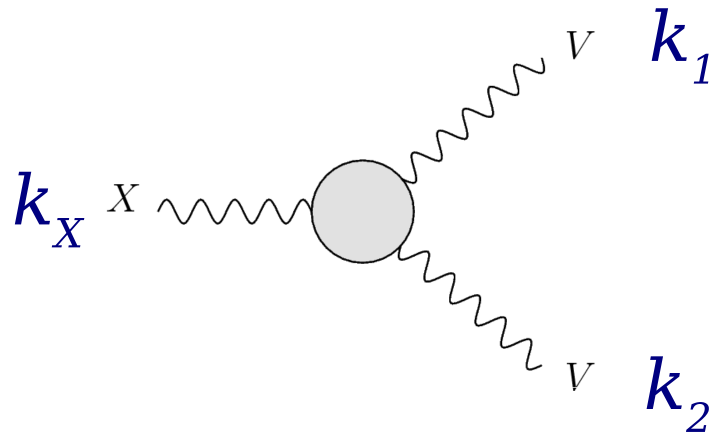
$$\mathcal{O}^1 = \frac{C_1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta}X_\mu Tr[\partial^\nu C_{\alpha\nu}C_{\beta\rho}]$$
$$\mathcal{O}^2 = \frac{C_2}{2\Lambda^2}\epsilon^{\mu\rho\alpha\beta}X_\mu \partial^\nu B_{\alpha\nu}B_{\beta\rho}$$

(Other possible terms vanish when requiring X on shell or when taking the trace)

From these two operators, it is straightforward to derive the vertex functions after EWSB.

Electroweak Effective Operator

XVV Electroweak Coupling



$$\Gamma^{XZZ}_{\mu\nu\rho}(k_X, k_1, k_2) = \frac{1}{\Lambda^2}(C_1 \cos^2\theta_W + C_2 \sin^2\theta_W)\Gamma_{\mu\nu\rho}(k_X, k_1, k_2)$$

$$\Gamma^{XZ\gamma}_{\mu\nu\rho}(k_X, k_1, k_2) = \frac{1}{\Lambda^2}(C_1 - C_2)\sin\theta_W \cos\theta_W \Gamma_{\mu\nu\rho}(k_X, k_1, k_2)$$

$$\Gamma^{XW^+W^-}_{\mu\nu\rho}(k_X, k_1, k_2) = \frac{C_1}{\Lambda^2}\Gamma_{\mu\nu\rho}(k_X, k_1, k_2)$$

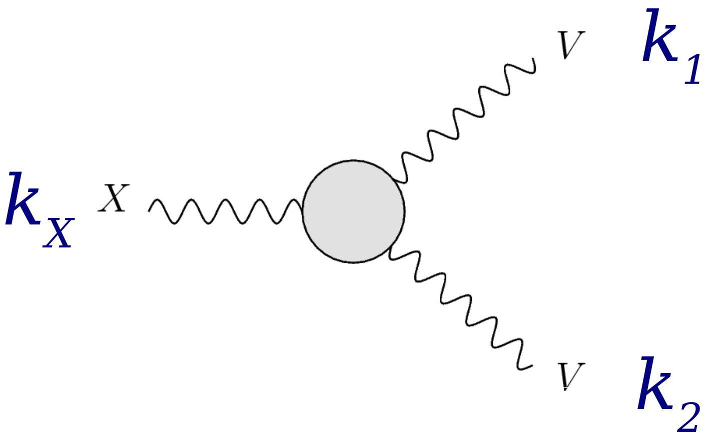
$$\Gamma^{X\gamma\gamma}_{\mu\nu\rho}(k_X, k_1, k_2) = \frac{1}{\Lambda^2}(C_1 \sin^2\theta_W + C_2 \cos^2\theta_W)\Gamma_{\mu\nu\rho}(k_X, k_1, k_2)$$

...where,

$$\Gamma_{\mu\nu\rho}(k_X, k_1, k_2) = \quad (k_{2\rho}\epsilon_{\mu\nu\sigma\tau}k_1^\sigma k_2^\tau - k_{1\nu}\epsilon_{\mu\rho\sigma\tau}k_1^\sigma k_2^\tau + \epsilon_{\mu\nu\rho\sigma}k_1^\sigma k_2 \cdot k_2 - \epsilon_{\mu\nu\rho\sigma}k_2^\sigma k_1 \cdot k_1)$$

Electroweak Effective Operator

XVV Electroweak Coupling



$$\Gamma^{XZZ}_{\mu\nu\rho}(k_X, k_1, k_2) = \frac{M_Z^2}{\Lambda^2}(C_1 \cos^2\theta_W + C_2 \sin^2\theta_W)\epsilon_{\mu\nu\rho\sigma}(k_1^\sigma - k_2^\sigma)$$

$$\Gamma^{XZ\gamma}_{\mu\nu\rho}(k_X, k_1, k_2) = \frac{M_Z^2}{\Lambda^2}(C_2 - C_1)\sin\theta_W \cos\theta_W \epsilon_{\mu\nu\rho\sigma}k_2^\sigma$$

$$\Gamma^{XWW}_{\mu\nu\rho}(k_X, k_1, k_2) = C_1 \frac{M_W^2}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma}(k_1^\sigma - k_2^\sigma)$$

$$\Gamma^{X\gamma\gamma}_{\mu\nu\rho}(k_X, k_1, k_2) = 0$$

(For all bosons on-shell)

X Partial Widths and Branching Fractions

$$\Gamma(X \to WW) = (42\ \mathrm{MeV}) \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4 \left(\frac{M_X}{\mathrm{TeV}}\right)^3 \left(1 - \frac{4M_W^2}{M_X^2}\right)^{5/2} C_1^2$$

$$\Gamma(X \to ZZ) = (16\ \mathrm{MeV}) \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4 \left(\frac{M_X}{\mathrm{TeV}}\right)^3 \left(1 - \frac{4M_Z^2}{M_X^2}\right)^{5/2} (C_1 + C_2 \tan^2\theta_W)^2$$

$$\Gamma(X \to \gamma Z) = (4.9\ \mathrm{MeV}) \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4 \left(\frac{M_X}{\mathrm{TeV}}\right)^3 \left(1 - \frac{M_Z^2}{M_X^2}\right)^3 \left(1 + \frac{M_Z^2}{M_X^2}\right) (C_2 - C_1)^2$$

Widths much smaller than mass. $\Rightarrow$ Narrow width approximation holds.

$\Rightarrow$ X mostly produced on-shell

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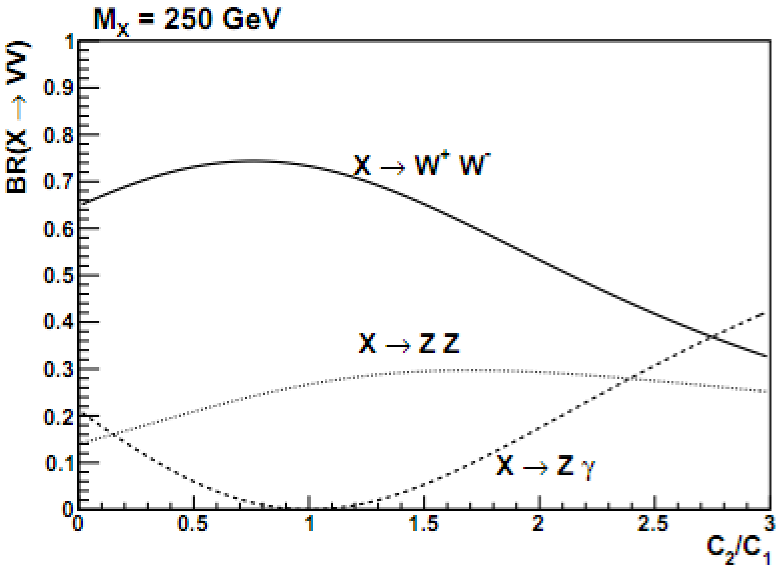

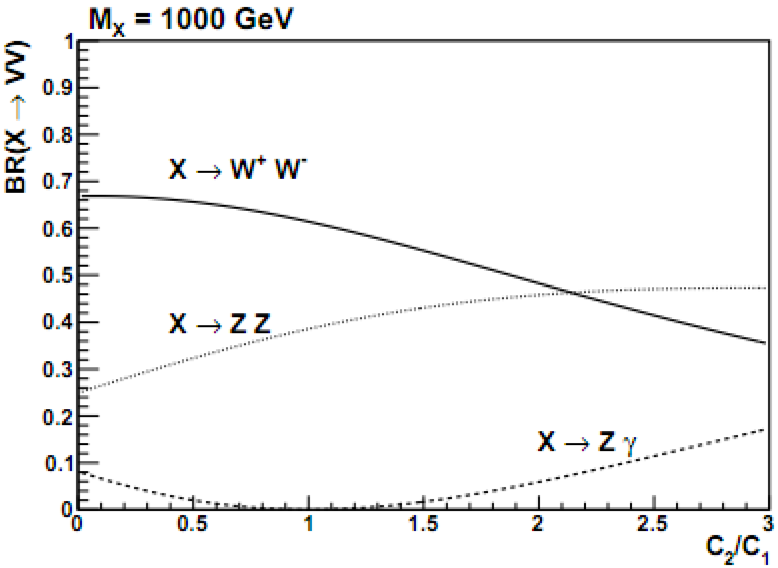

Collider Phenomenology

These 3-boson couplings lead to a variety of production and decay channels. We will study two channels in particular which maximize our sensitivity at the LHC.

→ Since LHC is a pp collider, production will be maximal though gluon and quark fusion processes.

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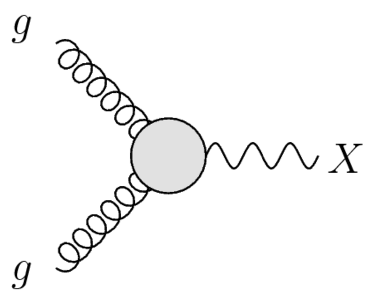
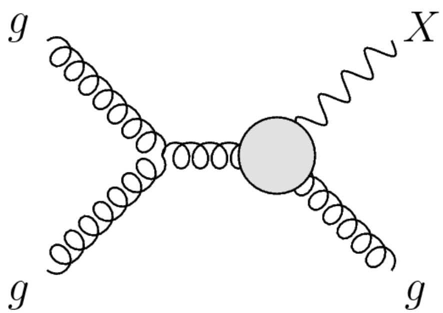
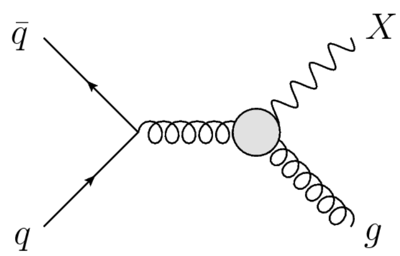
- Since LHC is a pp collider, production will be maximal though gluon and quark fusion processes.
- To avoid overwhelming backgrounds, we look at decays through electroweak couplings.
- To avoid overwhelming backgrounds, we look for leptons in the final state

Quark/Gluon Fusion Production

(External particles are assumed on-shell)







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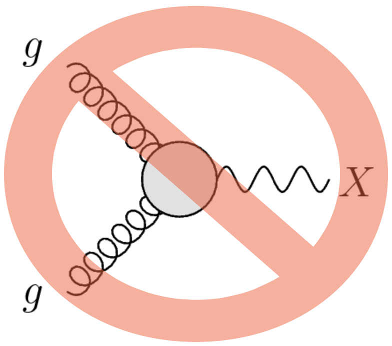
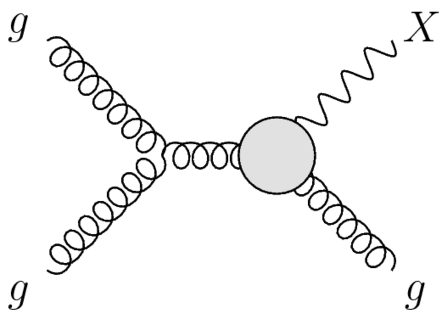
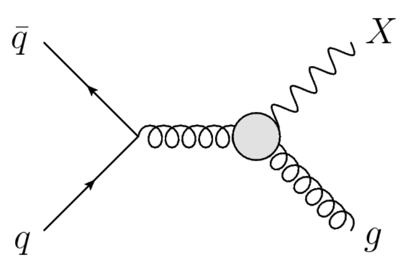


...as shown earlier (Landau-Yang theorem)





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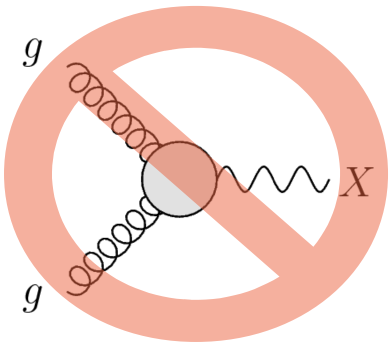

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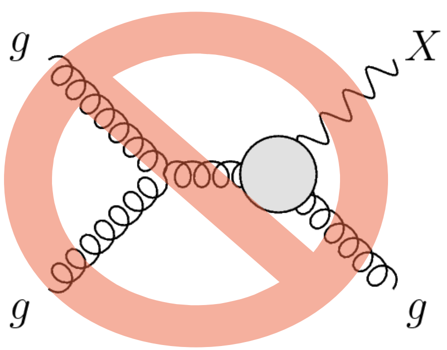
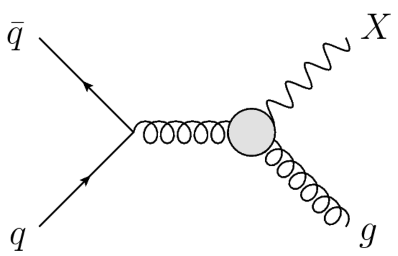


...also vanishes (after including the 4-point vertex).
(Perhaps due to a Yang theorem type of argument for a pseudovector?)



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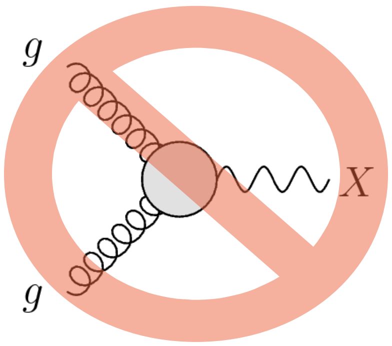

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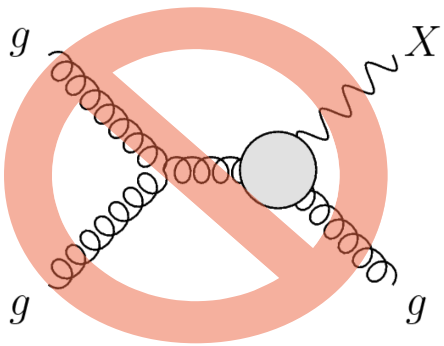

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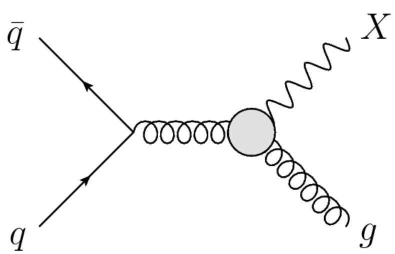

NONZERO
X is always produced with an associated jet.

$qg \to qX$ and $q\bar{q} \to gX$

Decay Channels

Remember that because the X-width is small compared to its mass, we treat the X to be on-shell. We also treat the decay products to be on-shell in order to reconstruct the invariant mass.

$$X \to gg$$

$$\mathcal{O}^1_{Xgg} = \frac{1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta}X_\mu D^\nu G^a_{\alpha\nu}G^a_{\beta\rho}$$

$$X \to \gamma\gamma$$

$$X \to ZZ$$

$$X \to Z\gamma$$

$$X \to W^+W^-$$

$$\mathcal{O}^1 = \frac{C_1}{\Lambda^2}\epsilon^{\mu\rho\alpha\beta}X_\mu Tr[\partial^\nu C_{\alpha\nu}C_{\beta\rho}]$$

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For X and decay products on-shell....
(Yang-Landau Theorem)

$$\cancel{X \rightarrow gg}$$

$$\cancel{X \rightarrow \gamma\gamma}$$

$$X \rightarrow ZZ$$

$$X \rightarrow Z\gamma$$

...and in order to reconstruct M_{Inv}

$$\cancel{X \rightarrow W^+W^-}$$

Note that we *could* have one of the daughter particles off-shell, leading to "three body decays" of the form

$$X \rightarrow gg^* \rightarrow gq\bar{q}$$

These processes, however, are highly suppressed by phase space factors in the decay rate formula

$$d\Gamma = \frac{1}{2m_{\mathcal{A}}}\underline{\left(\prod_f \frac{d^3p_f}{(2\pi)^3}\frac{1}{2E_f}\right)}\left|\mathcal{M}(m_{\mathcal{A}} \rightarrow \{p_f\})\right|^2 (2\pi)^4\delta^{(4)}(p_{\mathcal{A}} - \textstyle\sum p_f)$$

Also, the two signals we *will* study are generally much cleaner.

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$$\cancel{X \rightarrow gg}$$

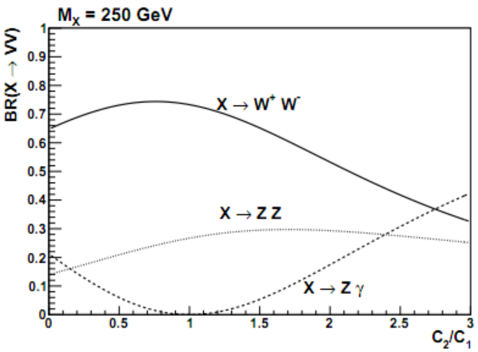
$$\cancel{X \rightarrow \gamma\gamma}$$

$$X \rightarrow ZZ \rightarrow l^+l^-l^+l^- \qquad \text{efficiency} = BR\{X \rightarrow ZZ\} \times 0.0045$$

$$X \rightarrow Z\gamma \rightarrow l^+l^-\gamma \qquad \text{efficiency} = BR\{X \rightarrow Z\gamma\} \times 0.067$$

...and in order to reconstruct M_{Inv}

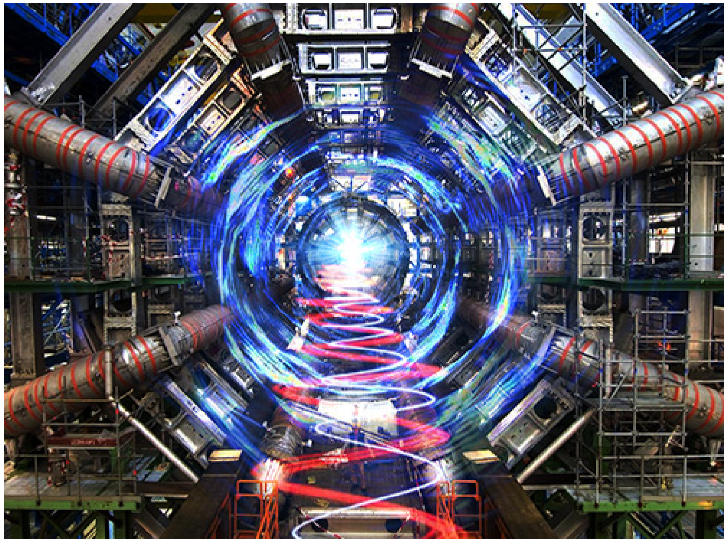
$$\cancel{X \rightarrow W^+W^-}$$



Search at the LHC

Q: So will we be able to see this signal at the LHC?

(obvious) A: That depends on M_X and scale Λ.



LHC in operation (artists rendering)

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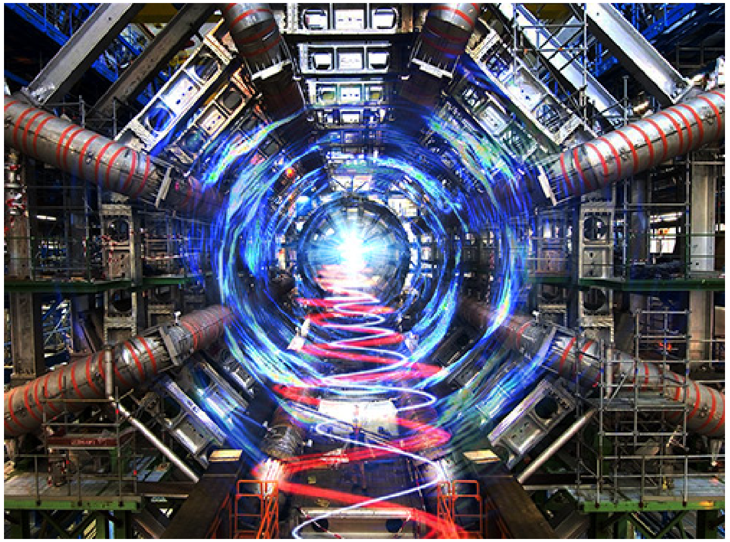


LHC in operation (artists rendering)

Analysis scheme

- Simulate events for a given Λ and various values of M_X
- Simulate background
- Apply cuts and determine cross sections of signal and BG
- Scale cross section (by scaling Λ) such that we have detection at LHC (for a certain luminosity)

↳ Scale lambda such that for a certain luminosity, there are *n* events such that...

$$\sigma = \frac{n}{\sqrt{n_{BG}}} \geq 5$$

If there are zero background events, require *n*=5.

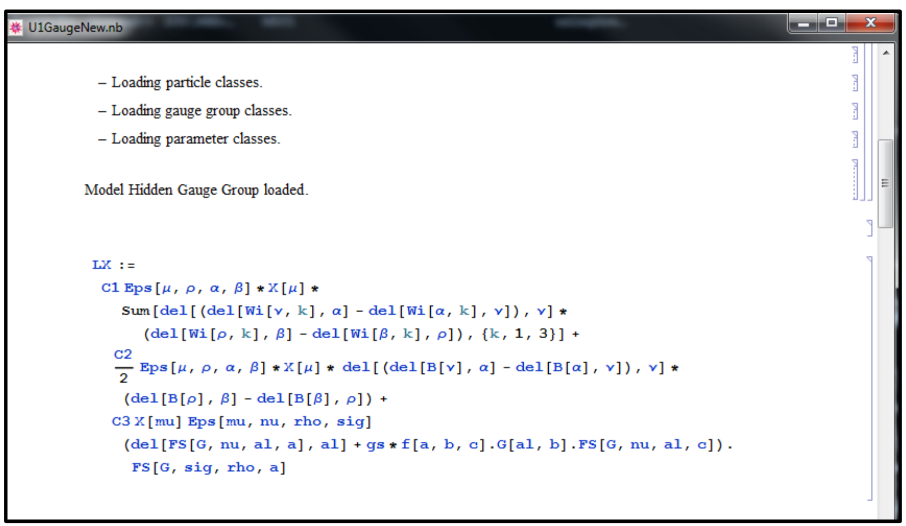
Scaled Λ is our "reach"

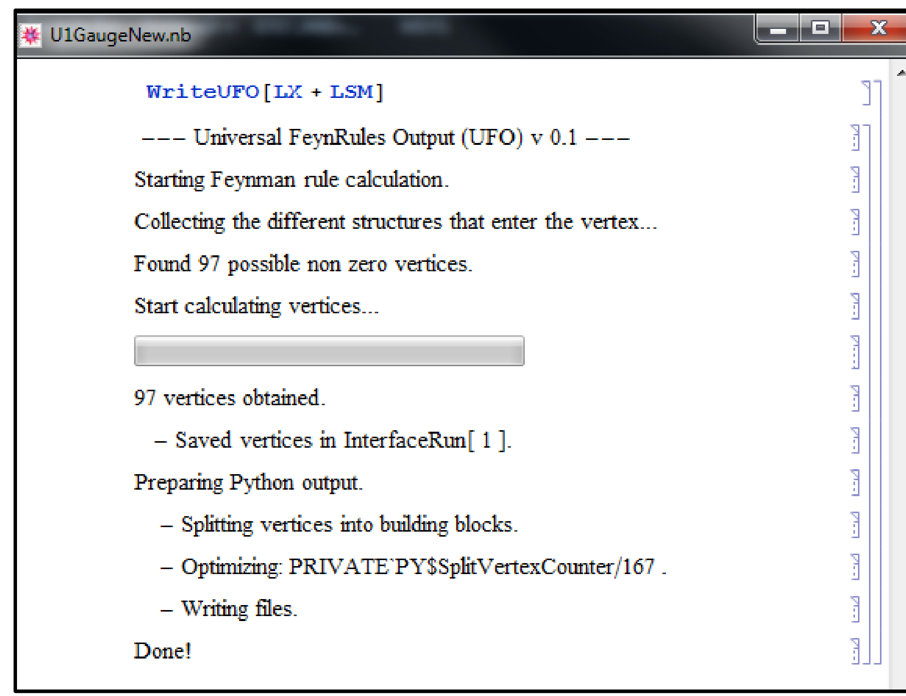
Simulation

Simulation chain

FeynRules → ALOHA/UFO → MadGraph5 → MadEvent → Pythia → PGS4

Recently released (2010/2011). Simplifies model building... Automatically translates Lagrangian into Python MG5 code.





Cuts

$X \to ZZ \to l^+ l^- l^+ l^-$	$X \to Z\gamma \to l^+ l^- \gamma$
4 leptons $p_T \geq 20$ GeV and $\lvert\eta\rvert \leq 2.5$	**2 leptons** $p_T \geq 20$ GeV and $\lvert\eta\rvert \leq 2.5$ **1 photon** $p_T \geq 10$ GeV
1 jet $p_T \geq 50$ GeV and $\lvert\eta\rvert \leq 2.5$	**1 jet** $p_T \geq 50$ GeV and $\lvert\eta\rvert \leq 2.5$
Leptons reconstruct to Zs (pairwise to 80 GeV $\leq m_{inv} \leq$ 100 GeV)	**Leptons reconstruct to Z** (80 GeV $\leq m_{inv} \leq$ 100 GeV)
All 4 leptons reconstruct to X (within 10% of M_X)	**Leptons and photon reconstruct to X** (within 10% of M_X)

These cuts drastically reduce standard model background. For almost all mass windows, and for luminosities up to 100fb^{-1}, we expect ZERO events!

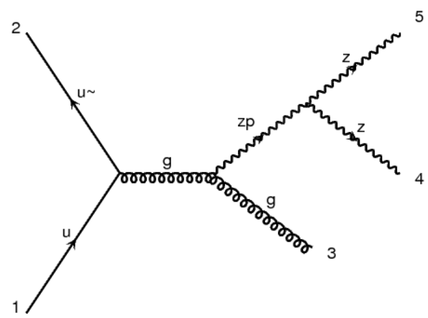
PLACE BACKGROUND PLOT HERE

$m_{central}$	$\sigma_{BG}(\mathrm{fb})$ $pp \to jl^+l^-l^+l^-$	$\sigma_{BG}(\mathrm{fb})$ $pp \to j\gamma l^+l^-$
250	0.2608	6.423
500	0.0500	0.7632
750	0.0104	0.1713
1000	0.0021	0.0339
1250	0.0004	0.0136
1500	0.0001	0.0051
1750	<0.0001	<0.0010
2000	<0.0001	<0.0010

Signal and Background

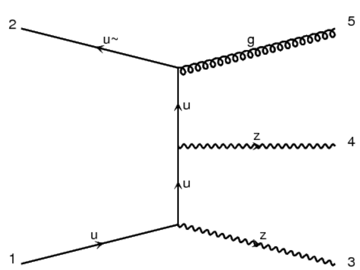
Invariant mass distribution
for signal...

$p\,p \rightarrow X\,j \rightarrow Z\,Z\,j$

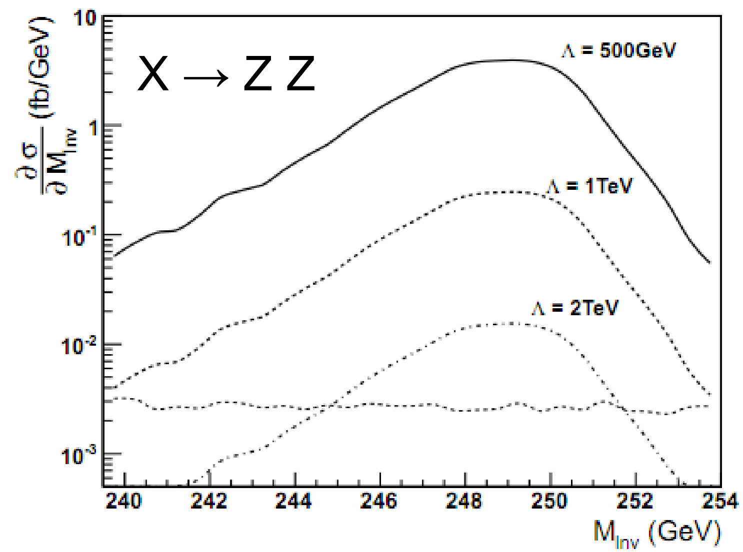


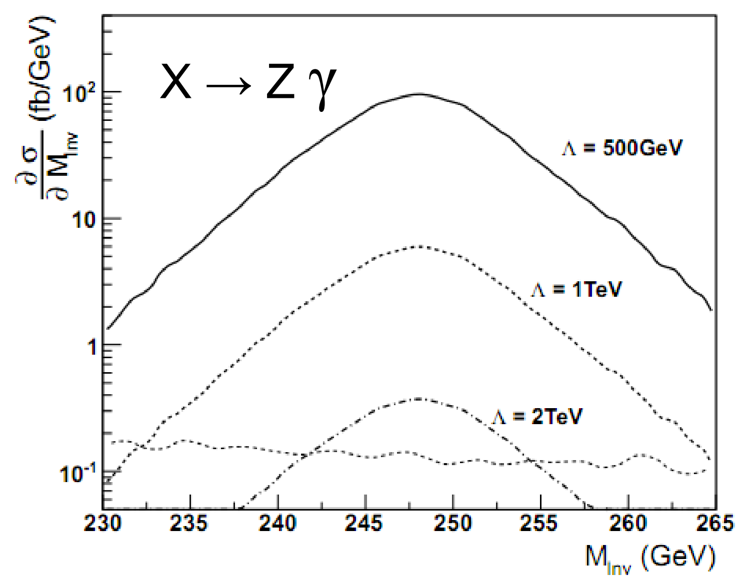
...and background

$p\,p \rightarrow Z\,Z\,i$



(One of MANY diagrams)

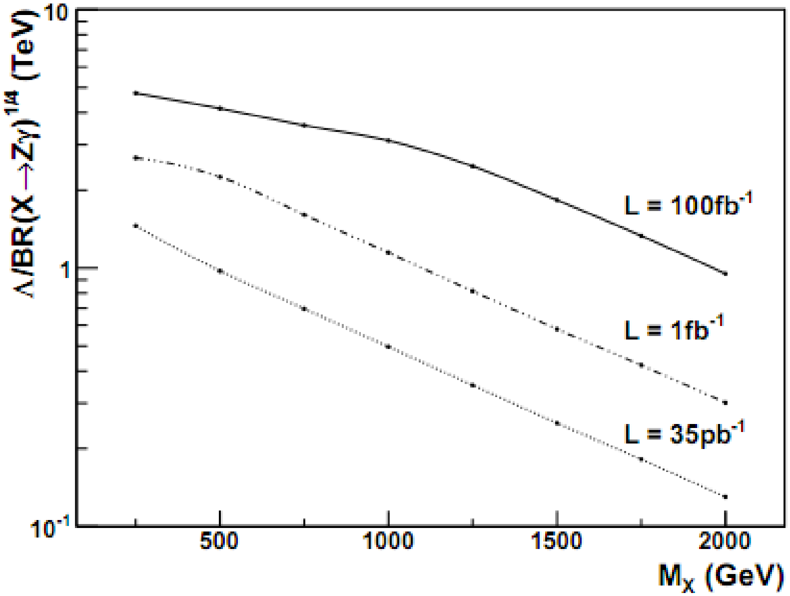


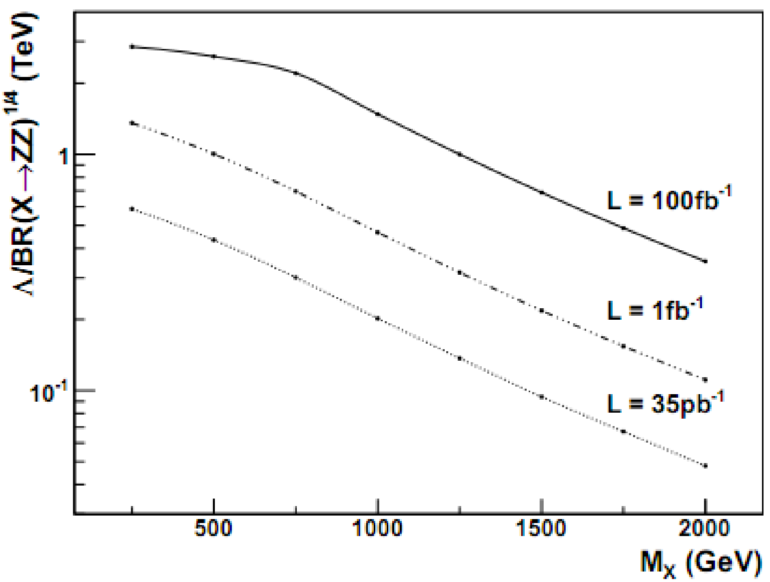


LHC Reach

Analysis shows we will be able to probe well into the TeV scale over the next few years as luminosity increases.

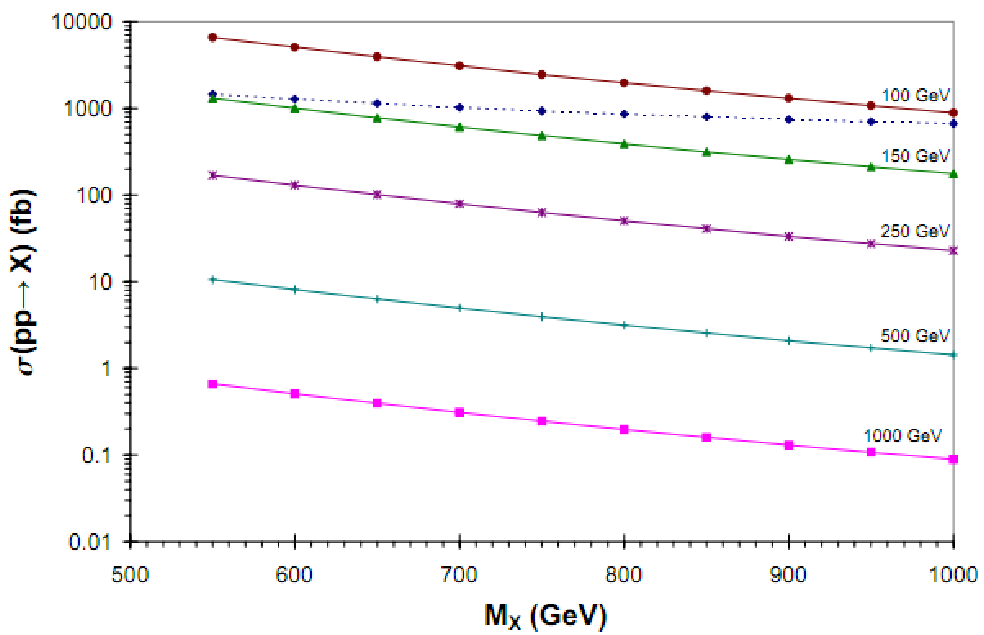
- $Z\gamma$ channel more sensitive (mainly due to the factor of BR^2 for the ZZ channel)
- ~3 fb^{-1} as of now (August '11). Can currently probe into TeV scale for M_X < 1TeV.
- For 14TeV, Λ-reach improves significantly
  - For M_X=1000GeV, 100fb^{-1} @ 14TeV gives roughly twice the reach in both channels
- Effective operator approach may break down when $M_X > \Lambda_X$





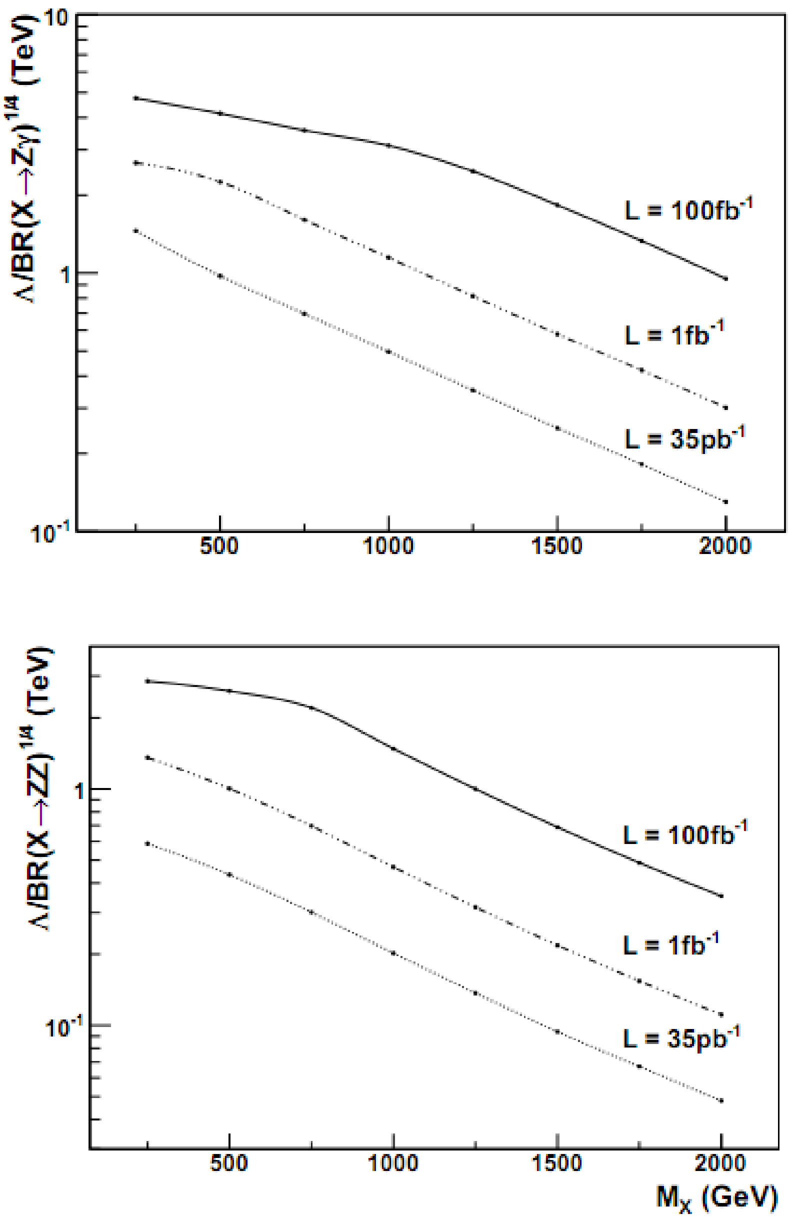
LHC Reach

For coupling only to SU(2), production can still proceed through vector boson fusion, but signal is drastically suppressed



Cross section for VBF production for different values of Λ_X. Dashed line indicates needed cross section for detection with 100fb^{-1} @ 14TeV.

Kumar, Rajaraman, Wells – arXiv:0707.3488



Signal Topology

Resonances decaying to ZZ or WW are signatures of heavy Higgs. Considering the very small branching ratio to leptons for heavy Higgs, we may have trouble distinguishing the signals.

How to we distinguish a pseudovector boson from other new physics?

- X requires the presence of an additional (hard) jet
- X will not decay to two massless vectors
- Absence of any leptonic channels
- Angle dependence of the associated jet/products??

A detailed study on distinguishing between pseudo-vector/vector/pseudo-scalar/scalar would be interesting. Can signal topology be used to separate these types?

Conclusions

- Higher order couplings can connect us to sectors otherwise out of reach of collider experiments.
- Hidden sectors that couple indirectly to both SU(3) and the electroweak sector lead to very clear signals at hadron colliders.
- The particular model of 3-boson axial couplings between an extra U(1) and the SM probe well into the TeV scale of new physics, even when the U(1) is *hidden* at tree level.
- Surprises are around the corner. Effective field theories can be useful in identifying phenomenological structure of the underlying theory of the new physics.

Thanks & Aloha